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THE PHYSICS OF SPIN-POLARIZED ATOMIC VAPORS.(U)
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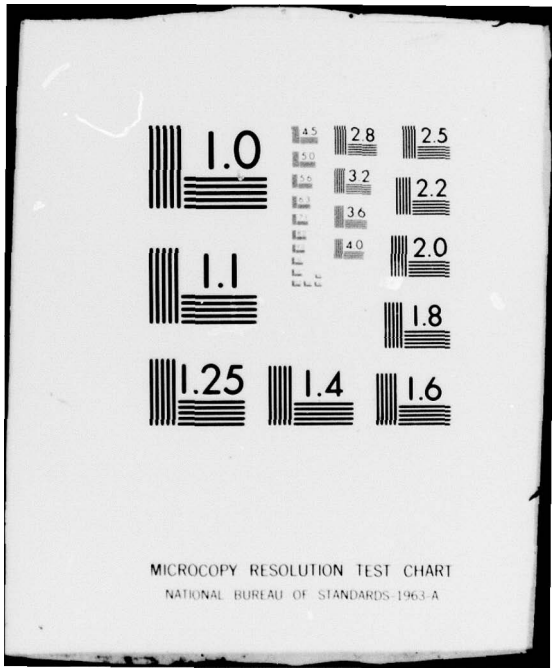
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CONTENTS

I. RESEARCH OBJECTIVES

The overall objective of the work supported by the Air Force Office of Scientific Research grant ~~AFOSR-74-2685~~ has been to explore the basic physical properties of spin polarized atomic vapors. These systems are of considerable interest to the civilian and military sectors of our society because they can be used to make very precise measurements of time, absolute rotation rates, and electromagnetic fields. For example, the U.S. time standard is the atomic cesium hyperfine frequency; very precise atomic frequency standards are used in satellites and on earth for a wide variety of uses. Optically pumped magnetometers are used by the oil and mining industry for prospecting, by archaeologists for locating lost cities and sunken treasure ships, and by the navy for location of submarines. Optically pumped systems are currently being developed for use as gyroscopes which may have real advantages in terms of ruggedness and economy.

In spite of the widespread practical utility of these systems, there is only limited research going on in related areas. There are no more than a dozen active research groups world wide and most are in foreign countries, including several excellent laboratories in the Soviet bloc.

The goal ~~of our~~ of this work ~~under grant AFOSR-74-2685~~ has been to maintain a center of excellence for the study of spin polarized atomic vapors, to ensure that outstanding students are introduced to the field from time to time and to coordinate our research activities with the needs of industrial and government laboratories for critical information and the needs of the university for high-quality basic research.

II. ACCOMPLISHMENTS

Some of the most important accomplishments which have resulted from work supported by grant AFOSR-74-2685 are listed below. While the main thrust of our effort has been the study of spin-polarized atomic vapors, accidental discoveries during the course of this work have led to several new lines of research, some of which are now receiving independent support from other agencies.

A. Spin Exchange in Alkali Vapors

Alkali vapors are one of the most important media for optically pumped devices because of their long spin relaxation times and relatively high vapor pressures. They are subject to a fundamental limit in density because of alkali-alkali collisions. The major effect of such collisions is to exchange the electron spins of the atoms while leaving the nuclear spins unaffected. There may be additional weaker interactions, but there is no unambiguous evidence for mechanisms other than spin exchange so far.

Since these spin exchange collisions limit the precision of optically pumped devices we have devoted quite a bit of effort toward understanding their consequences. One of our most significant accomplishments has been the discovery of a curious spin exchange narrowing and shifting of magnetic resonance lines. This occurs at very high spin exchange rates and therefore in very dense alkali vapors. Thus, we were led to the study of very dense vapors by our interest in spin exchange. One consequence has been a number of unexpected discoveries. For example, we accidentally discovered the curious photochemical reaction between optically excited alkali atoms and hydrogen gas which leads to the production of alkali hydride crystals in a

laser beam. This work has attracted considerable interest and has received separate funding from the National Science Foundation. Our work on high density vapors also led to the discovery of visible excimer emission bands from alkali noble gas excimers and this work has received separate funding from the Army Research Office.

B. Properties of Excited Alkali Atoms

To spin polarize an atom by optical pumping it is necessary to pump the atom into an excited state from whence it decays by spontaneous radiation. The evolution of the excited atom under the influence of hyperfine coupling, collisional effects and external magnetic fields has a profound influence on the optical pumping efficiency. We have devoted a certain fraction of our time to the study of these excited-state properties, and we have greatly increased the understanding excited state hyperfine structure and relaxation. This work has been published in a series of articles in the Physical Review, the Physical Review Letters and other journals. Members of our research group have given invited papers on our findings in numerous international scientific conferences.

C. Magnetic Field Display of Radiofrequency Spectrum

We have developed a novel method to display the radiofrequency spectrum of an unknown source by use of an optically pumped vapor in a magnetic field gradient. Some interest has been expressed in using this device as a frequency analyzer to replace much more elaborate conventional devices.

D. Attraction and Repulsion of Light Beams in an Atomic Vapor

We have discovered a curious interaction between light beams which is mediated by the atoms of an optically pumped vapor. The pumped atoms fly

freely between laser beams and they transmit a force which can be positive or negative, depending on the relative polarization of the beams. This work has attracted widespread interest and we have given invited papers on the subject at international conferences.

E. Optical Pumping of Atoms in Flames

We have demonstrated that it is possible to spin polarize sodium atoms by optically pumping them in a flame at ordinary atmospheric pressure. One curious result of this work is that the spin relaxation rates were found to be minimum in the sooty reducing regions of the flame. This new probe technique shows considerable promise for diagnostics of combustion processes.

III. JOURNAL ARTICLES PUBLISHED

BETWEEN NOVEMBER 1, 1973 AND FEBRUARY 28, 1979

K. H. Liao, R. Gupta, and W. Happer, "Measurement of Hyperfine Structure of the $4^2S_{1/2}$ State of Na^{23} by Cascade Radio-Frequency Spectrosocpy," Phys. Rev. A8, 2811 (1973).

R. Gupta, W. Happer, L. K. Lam, and S. Svanberg, "Hyperfine-Structure Measurements of Excited S States of the Stable Isotopes of Potassium, Rubidium, and Cesium by Cascade Radio-Frequency Spectrosopy," Phys. Rev. A8, 2792 (1973).

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Andrew C. Tam, "Stepwise Excitation and Level-Crossing Spectroscopy of the Triplet D States of Helium-4," Phys. Rev. A 12, 539 (1975).

A. C. Tam and W. Happer, " Spectroscopy of the CsH ($X^1\Sigma^+$) State by Laser-excited Fluorescence," J. Chem. Phys. 64, 2456 (1976).

A. C. Tam, G. Moe, B. R. Bulos, and W. Happer, "Excimer Radiation from Na-noble-gas and K-noble-gas Molecules," Opt. Comm. 16, 376 (1976).

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A. C. Tam and G. W. Moe, "Emission Bands from Discharge Excited Alkali-Noble-Gas Systems," Phys. Rev. A 14, 528 (1976).

A. C. Tam and C. K. Au, "Polarization Reversal of Rayleigh Scattering Near a $^2P_{3/2,1/2}$-$^2S_{1/2}$ Resonance Doublet," Optics Comm. 19, 265 (1976).

Andrew C. Tam, "Fine-structure Intervals in the 3^3P and n^3D States of ^4He," J. Phys. B: Atom. Molec. Phys. 9, L559 (1976).

A. C. Tam and W. Happer, "Long-Range Interactions between cw Self-Focused Laser Beams in an Atomic Vapor," Phys. Rev. Letters 38, 278 (1977).

A. C. Tam and W. Happer, "Optically Pumped Cell for Novel Visible Decay of Inhomogeneous Magnetic Field or of RF Frequency Spectrum," Applied Phys. Lett. 30, 580 (1977).

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A. Tam, "Optical Pumping of a Dense $Na+He+N_2$ System: Application as an rf Spectrum Analyzer," J. Appl. Phys. 50, 1171 (1979).

IV. PAPERS PRESENTED AT SCIENTIFIC CONFERENCES

R. Gupta, "Measurement of Atomic Parameters of the Optically Inaccessible States by Cascade-Fluorescence Spectroscopy," Invited Paper, Fourth Annual Meeting of the Division of Electron and Atomic Physics of the American Physical Society, Stanford Research Institute, Menlo Park, California, November 29 - December 1, 1972, Bull. Am. Phys. Soc. II 17, 1127 (1972).

A. Tam, H. Tang, and W. Happer, "Quenching Effect of He 2-μ Light on a Weak He Discharge," Twenty-Fifth Annual Gaseous Electronics Meeting of the American Physical Society, London, Ontario, Canada, October 17-20, 1972, Bull. Am. Phys. Soc. II 18, 808 (1973).

C. Tai, R. Gupta, and W. Happer, "Hyperfine Structure of Cs^{133} 6^2D State by Cascade-Fluorescence Spectroscopy," American Physical Society Meeting, New York, New York, January 29 - February 1, 1973, Bull. Am. Phys. Soc. II 18, 121 (1973).

L. K. Lam, R. Gupta, and W. Happer, "Hyperfine Structures of the First Excited S and D States of Rb and Cs," American Physical Society Meeting, New York, New York, January 29 - February 1, 1973, Bull. Am. Phys. Soc. II 18, 121 (1973).

S. R. Svanberg, P. Tsekeris, and W. Happer, "Two-Step Optical Excitation of Highly Excited S and D Levels in Alkali Atoms for Hyperfine Structure Studies," American Physical Society Meeting, Washington, D.C., April 23-26, 1973, Bull. Am. Phys. Soc. II 18, 611 (1973).

S. Svanberg, "Spectroscopy of Highly Excited Levels in Alkali Atoms Using a cw Dye Laser," Invited Paper, Laser Spectroscopy Conference, Vail, Colorado, June 25-29, 1973 (Proceedings to be published by Plenum Press).

R. Gupta, "Non-P Excited States of the Alkali Atoms," Invited Paper, Fifth Annual Meeting of the Division of Electron and Atomic Physics, New Haven, Connecticut, December 10-12, 1973, Bull. Am. Phys. Soc. II 18, 1499 (1973).

G. W. Moe and W. Happer, "Magnetic Circular Dichroism of Pressure Broadened Absorption Lines," Second International Conference on Spectral Lines, Eugene, Oregon, August 26-30, 1974.

R. Gupta, "Hyperfine Structure of the Highly Excited States of Alkali Atoms," IX International Conference on the Physics of Electronic and Atomic Collisions, University of Washington, Seattle, Washington, July 24-30, 1975.

R. Gupta, "Spectroscopy of the Non-P States of Alkali Atoms," Atomic Spectroscopy Symposium, National Bureau of Standards, Gaithersburg, Maryland, September 23-26, 1975.

W. Happer, "Laser Snow: Particle Formation by Resonant Light," IXth International Conference on Quantum Electronics, Amsterdam, The Netherlands, June 15, 1976.

R. Gupta, "Hyperfine Structures in the Excited States of Alkali-Metal Atoms," Fourth International Conference on Hyperfine Interactions, Madison, New Jersey, June 13, 1977.

W. Happer, "Long Range Interactions Between CW Laser Beams," Third International Conference on Laser Spectroscopy, Jackson, Wyoming, July 8, 1977.

W. Happer, "États Atomique et Moleculaires Couplés a un Continuum; Atomes et Molécules Hautement Excités," Colloque Internationale du CNRS, France, June 13-17, 1977.

V. COLLOQUIA, SEMINARS AND LECTURES

PRESENTED BY PERSONNEL OF GRANT AFOSR-74-2685

R. Gupta, "Cascade-Fluorescence Spectrosocpy on Optically Inaccessible Atomic States," Colloquium, Department of Physics, Reading University, Reading, England, February 14, 1973.

W. Happer, "Highly Excited Alkali Atoms," Seminar, Department of Physics, Texas A&M University, College Station, Texas, January 11, 1973; Colloquium, Department of Physics, Rice University, Houston, Texas, January 12, 1973; Seminar, Department of Physics, University of California, Berkeley, California, February 28, 1973.

S. Svanberg, "Optical Double-Resonance and Level-Crossing Experiments at Chalmers University of Technology, Goteborg, Sweden," Seminar, Department of Physics, New York University, New York, New York, February 26, 1973.

S. Svanberg, "Hyperfine Structure Investigations of Excited Levels in Alkali Atoms," Seminar, Department of Physics, University of Connecticut, Storrs, Connecticut, May 14, 1973.

R. Gupta, "Cascade Fluorescence Spectroscopy," Seminar, Department of Physics, City College of the CCNY, New York, New York, February 15, 1974.

W. Happer, "Miniature Magnetometers," Colloquium, U. S. Naval Ordnance Laboratory, Washington, D.C., February 5, 1974.

W. Happer, "Cold Spins in Hot Alkali Vapors," Colloquium, Department of Physics, University of Connecticut, Storrs, Connecticut, March 15, 1974; Colloquium, University of Tennesse, Knoxville, Tennessee, April 2, 1974.

A. Tam, "Stepwise Excitation and Level Crossing Spectroscopy of the Triplet D States of ^{4}He," Seminar, Department of Physics, Columbia University, New York, New York, January 31, 1975.

A. C. Tam, "Interaction of Laser-beam with Dense Alkali Vapors-Recent Development," Colloquium, University of South Carolina at Columbia, Columbia, South Carolina, November 23, 1976.

A. C. Tam, "Bouncing Laser Beams and Laser-Snow," Seminar, Brookhaven National Laboratory, Upton, New York, March 31, 1977.

A. C. Tam, "Bouncing Laser Beams and Glowing Laser-produced Plasma," Seminar, Bell Laboratories, Murray Hill, New Jersey, April 14, 1977.

R. Gupta, "Excited States of Alkali Atoms," Colloquium, Wesleyan University, Middletown, Connecticut, October 28, 1976; Colloquium, Kansas State University, Manhattan, Kansas, February 22, 1977; Colloquium, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, May 13, 1977.

W. Happer, "Laser Snow," University of California at Santa Barbara, February 16, 1977; Allied Chemical Research Labs, Morristown, New Jersey, March 14, 1977; Wesleyan University, April 7, 1977; Harvard University, Cambridge, Massachusetts, May 23, 1977.

W. Happer, "Highly Excited Alkali Inert Gas Excimers," Aussois France, June 15, 1977; Paris Observatory, June 10, 1977.

A. C. Tam, "Long Range Interaction Between Laser Beams in an Atomic Vapor," Gordon Research Conference (Atomic Physics) Brewster Academy, Wolfeboro, New Hampshire, July 4-8, 1977.

A. C. Tam, "Plasma Production in Cs Vapor by a Weak CW Laser Beam at 6010 A," Gordon Research Conference (Nonlinear Effects and Lasers), Holderness School, New Hampshire, August 15-19, 1977.

W. Happer, "Highly Excited Alkali-Noble Gas Excimers," Meudon Observatory, Paris, France, June 10, 1977.

W. Happer, "Long Range Interactions Between cw Self-Focused Laser Beams in an Atomic Vapor," University of Rochester, Rochester, New York, November 8, 1977; Thomas J. Watson IBM Research Center, Yorktown Heights, New York, November 17, 1977.

A. C. Tam, "Forces Between Laser Beams," Seminar, Columbia Radiation Laboratory, New York, New York, June, 1977; Colloquium, Columbia University, New York, New York, November, 1977; Seminar, New York University, New York, New York, December, 1977.

A. C. Tam, "Display-Magnetometers and Spectrometers," Seminar, Massachusetts Institute of Technology, Cambridge, Massachusetts, October 1977; Seminar, University of Massachusetts, Amherst, Massachusetts, November, 1977.

S. M. Curry, "Excitation Transfer Reactions in Laser-Excited Cesium Vapor," Seminar, University of Connecticut, Storrs, Connecticut, March 6, 1978.

S. M. Curry, "Laser-Induced Plasma Formation in Cesium Vapor: An Atomic Chain Reaction," Colloquium, University of Arkansas, Fayettesville, Arkansas, March 24, 1978.

W. Happer, "Laser Photochemistry of Alkali Vapor Hydrogen System," Seminar, Exxon Research Laboratories, December 21, 1978.

W. Happer, "Laser Snow," Department of Physics, Texas A & M University, October 19, 1978; Department of Physics, University of Texas at Dallas, February 1, 1979; JILA Colloquium, University of Colorado, March 8, 1979.

VI. PERSONNEL

Many excellent young scientists have received their training with support from Grant AFOSR-74-2685 at Columbia. They are now continuing to contribute to the technological base of the United States in government, industry and the universities. Senior research staff and graduate students are listed below.

Senior Research Staff

W. Happer (principal investigator at Columbia University).

R. Gupta (now at University of Arkansas; spent one year at Wright Patterson Avionics Laboratory as exchange scientist from Columbia).

S. Svanberg (now at Chalmers University in Sweden).

G. Moe (now at Riverside Research Institute in Manhattan).

A. Tam (now at Bell Telephone Laboratories in Murray Hill, New Jersey).

S. M. Curry (now in electronics research in Dallas, Texas).

T. Yabuzaki (now at Kyoto University, Japan).

N. Bhaskar (now at Columbia University).

Graduate Students

L. Lam Ph.D. 1973; now at University of Southern California.

J. Farley Ph.D. 1974; now at University of Arizona.

K. Liao Ph.D. 1974; now at Xerox Corporation.

C. Tai, Ph.D. 1974; now at University of British Columbia.

A. Tam, Ph.D. 1974; now at Bell Telephone Laboratories.

P. Tsekeris Ph.D. 1974; now at Ioannina University in Greece.

W. Park Ph.D. 1978; now at Plasma Physics Laboratory, Princeton, New Jersey.

M. Hou Student at Columbia University.

VII. INTERACTIONS OF RESEARCH STAFF WITH THE SCIENTIFIC AND TECHNOLOGICAL COMMUNITY

Personnel involved in Grant AFOSR-74-2685 have had many fruitful interactions with other programs of interest to the Air Force. Dr. Happer serves as a consultant to several research groups in industry which are working on optically pumped gyroscopes with Air Force or internal support. He has contributed to the work on the mercury gyroscope at Kearfott Singer, to the work on the xenon-krypton gyroscope at Litton Industries, and to the work on mercury gyroscopes at Bendix. He has also advised the Air Force and other parts of the Department of Defense through his work in the consulting group JASON. He has also been quite closely involved with nonacoustic submarine detection for the Navy. All of this work has benefitted from the research supported by Grant AFOSR-74-2685 at Columbia.

Dr. Gupta spent a year at the Avionics Laboratory at Wright Patterson Air Force Base in 1977. He was able to apply some of the skills he acquired at Columbia to studies of combustion in aircraft engines.

Dr. Moe has joined the Riverside Research Institute where he is working on submarine detection under contract to the Navy. He has made good use of experience he gained at Columbia.

Dr. Tam is a member of the technical staff at Bell Telephone Laboratories where he is valued highly as an unusually imaginative young scientist.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A review of some of the main achievements of work on spin polarized alkali vapors and their relevance to magnetometers, gyroscopes and other devices is presented. Personnel histories, scientific publications and interactions within the technical community are also summarized.

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